Measurement of Phase Distortion *

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This paper deals with the measurement of phase distortion or delay distortion and is particularly concerned with measurements on telephone circuits. For this purpose, use is made of a quantity defined as "envelope delay," which is the first derivative of the phase shift with respect to frequency. Various methods for measuring this quantity and the principles on which they are based are discussed, the details of the measuring circuits being omitted and sources of further information referred to when possible. Data are included which give the measured envelope delay-frequency characteristics of several kinds of telephone circuits.

AT an early date in the use of long loaded telephone circuits, certain disturbing effects at high frequencies were noticed which have been known as transients.[1] It was found that on such circuits, even when the attenuation was very carefully equalized within the transmitted range, these transient effects still persisted and were made worse. It was realized that these effects were due to phase distortion or delay distortion, that is, the resultant effect of phase shift varying with frequency in a peculiar manner. It was also determined that these effects resulted largely from the loading associated with the circuit pairs and that the effect could be considerably reduced by using a much lighter loading for the circuits.[2] Lighter loading systems were applied to telephone circuits so that as a result these transient effects were minimized to such an extent as to make circuits commercial for telephone use.

Recent developments in telephone transmission and in special services requiring the use of telephone circuits have emphasized these high-frequency effects due to phase distortion and have indicated a similar effect at low frequencies which results from the equipment associated with the circuit. The use of loaded cable circuits in place of open-wire circuits, with a corresponding increase in the number of repeaters, has increased the phase distortion considerably on telephone circuits. This is particularly true when very long telephone circuits in cable result so that these effects are quite disturbing. Certain special uses to which circuits have been put within the last five or six years require either a much wider band of frequencies for transmission, or can allow only a very small amount of distortion within the required band. Circuits which would ordinarily be satisfactory for telephone use are not good enough for these purposes.

* Presented at New York Section, A. I. E. E., May 1930.

[1] "Telephone Transmission of Long Cable Circuits," A. B. Clark, *Jour. A. I. E. E.*, Vol. XLII, p. 1, 1923, and *B. S. T. J.*, Vol. II, p. 67, 1923.

[2] J. R. Carson, A. B. Clark, J. Mills, U. S. Patent 1,564,201.

For example, telephotography,[3] which requires a relatively narrow band of frequencies, can allow so little phase distortion within this band for satisfactory transmission of a picture, that the use of H-174* side circuits for distances greater than about 100 miles requires the use of some means for correcting the phase distortion introduced by the loading on the cable pairs. The transmission of programs for the interconnection of radio broadcasting stations requires a wide frequency band for satisfactory quality; and unless corrected, effects due to phase distortion outside the usual telephone range of frequencies, which would not be very disturbing for telephone conversation, make the program transmitted unsatisfactory to the listener. Television, of course, with its very wide frequency band and its very rigid requirements regarding phase distortion, does not allow even the use of open wire circuits for its transmission for any great distance without the aid of phase correction.[4]

It is the purpose of this paper to describe and discuss various methods which have been devised for the measurement of phase distortion. Phase distortion and its effects, as well as methods of correcting for it [5, 6, 7, 8], are considered here only sufficiently for the understanding of these measuring means. It is, of course, necessary that before the correction can be designed, the amount of distortion be known, and that, after the corrective apparatus has been built and applied to the circuit, the overall system be checked to find out how complete the correction has been. The devices described below are for this particular purpose, and before describing them, the fundamental theory upon which they are based will be considered. Some of the principles underlying particular methods of measurement will be considered in the description of the devices themselves.

After the discussion of the various measuring devices, certain data will be given which give the results of various measurements made on actual telephone circuits with some of these measuring devices.

[3] "The Transmission of Pictures over Telephone Lines," H. E. Ives, J. W. Horton, R. D. Parker, A. B. Clark, *B. S. T. J.*, Vol. IV., p. 187, 1925.

* In designating loading systems, the initial letter denotes spacing, *H* denoting 6000 feet and *B* denoting 3000 feet; the first number denotes the inductance of the loading unit in the side circuit in millihenries; a second number denotes the inductance of the loading unit in the phantom circuit in millihenries; the letter *N* following the number denotes non-phantomed pairs.

[4] "Wire Transmission System for Television," D. K. Gannett and E. I. Green, *A. I. E. E. Transactions*, Vol. XLVI, p. 946, 1927 and *B. S. T. J.*, Vol. VI, p. 616, 1927.

[5] "Phase Distortion and Phase Distortion Correction," Sallie Pero Mead, *B. S. T. J.*, Vol. VII, p. 195, 1928.

[6] "Distortion Correction in Electrical Circuits with Constant Resistance Recurrent Networks," O. J. Zobel, *B. S. T. J.*, Vol. VII, p. 438, 1928.

[7] "Phase Distortion in Telephone Apparatus," a companion paper by C. E. Lane.

[8] "Effects of Phase Distortion on Telephone Quality," a companion paper by J. C. Steinberg.

Theory Underlying Phase Distortion Measurement

It should be understood that what is meant here by phase shift is really the insertion phase shift; that is, the phase shift of a system is the change in phase at the receiving terminal due to the insertion of the system under consideration between the generator and the receiving terminal. In the same way, when delays are mentioned, insertion delays are understood unless otherwise specified.

A certain amount of time is required for the transmission of any signal from one place to another; and it has been found that, for a natural reproduction of tone or speech, or the satisfactory transmission of any signal, not only must the attenuation of the various component frequencies be approximately equalized, but also the time of propagation of these same component parts must be nearly the same for different frequencies. This time of propagation is, of course, closely related to the change in phase of the component frequencies during transmission.

In order to have no phase distortion it is necessary that the phase shift be linear with frequency within the frequency range required for transmission.[5,7] Graphically, this means that if the phase shift is plotted as a function of frequency, the resulting graph will be a straight line within the frequency range under consideration. It is evident then that for such a condition the first derivative of the phase shift with respect to frequency, or the slope of the phase shift-frequency curve, is constant.

The slope or first derivative is closely related to the delay of the envelope. The following statement results from a mathematical consideration of the building up of sinusoidal currents in systems similar to those which we are considering here.[9] *The envelope of the oscillations in response to an e.m.f. $E \cos \omega t$ applied at time $t = 0$ reaches 50 per cent of its ultimate steady value at time $t = d\beta/d\omega$ and its rate of building up is inversely proportional to $\sqrt{d^2\beta/d\omega^2}$.* Various assumptions are made in arriving at this conclusion, but it does not seem necessary to discuss these here except to mention the condition that the attenuation of the system under consideration should be approximately equalized over the frequency range in the neighborhood of the applied frequency.

It is apparent then that this quantity $d\beta/d\omega$ plays a fundamental rôle in determining the delay of a system. Moreover, the use of $d\beta/d\omega$ has an advantage over β in that it is constant for a distortionless system, while β varies with frequency. The quantity $d\beta/d\omega$ will simply be defined here as the "envelope delay" of a system in frequency

[9] "Building Up of Sinusoidal Currents in Long Periodically Loaded Lines," J. R. Carson, *B. S. T. J.*, Vol. III, p. 558, 1924.

ranges where the attenuation is not a function of frequency; that is, the envelope delay in seconds is

$$T = \frac{d\beta}{d\omega} = \frac{dB}{df},$$

where

$\beta =$ the phase shift measured in radians,

$B =$ the phase shift measured in cycles,

$f =$ the frequency measured in cycles per second,

and

$\omega = 2\pi f.$

Hereafter in this paper this notation will be used.

For a distortionless system this quantity is the actual delay of the signal transmitted through the system. However, for a system which introduces phase distortion, the received envelope is usually quite different from the impressed envelope; and the delay of this envelope through the system is then quite indefinite depending upon what particular feature of the envelope is taken for observation. Nevertheless, the quantity defined as envelope delay is perfectly definite for such a system.

The significance of phase shift and envelope delay and the relation between the two is considered at some length in other papers.[6*, 7] The use of phase shift and delay data as a measure of phase distortion is also considered there. Phase shift itself is a rather fundamental quantity and various means of measuring it can be devised when both ends of the system under consideration are available. In this paper, one method of doing this is referred to which has proved very useful in laboratory measurements in the design of apparatus. However, for field measurements on telephone circuits, envelope delay seems to be a more useful quantity with which to work. The derived nature of this quantity makes its measurement somewhat complicated and consequently considerable space is given to methods for this purpose.

The envelope delay is determined from the difference in the steady-state phase shift for a definite interval of frequency. In practical cases finite intervals are used instead of infinitesimally small intervals which would be required for the determination of the derivative, or of the slope of the phase shift-frequency curve. This means then that the measured value is actually the slope of the secant of the curve and is simply an approximate value for the envelope delay, the amount of approximation depending on the size of the interval chosen. The value of envelope delay arrived at in this way will be called T_Δ so that

[6*] l.c. Appendix I.

$$T_\Delta = \frac{\Delta\beta}{\Delta\omega} = \frac{\Delta B}{\Delta f},$$

where $\Delta\beta$ represents a finite difference in β, etc.

The use of steady-state conditions for the measurements of envelope delay * has quite evident advantages practically over a method which would tend to measure the delay of the envelope itself in a transient state.

Methods of Measurement

In making measurements of phase shift or envelope delay for the purpose of determining the phase distortion of a telephone system, it should be borne in mind that the absolute value is usually of small importance and that the chief purpose is to determine the relative values from one frequency to another; that is, the characteristic of the phase shift or delay with frequency is the desired information as regards phase distortion.

1. *Measurement of Phase Shift*

The first method of measurement described here will be one which may be used to measure the phase shift itself.[10] Fig. 1 shows schemati-

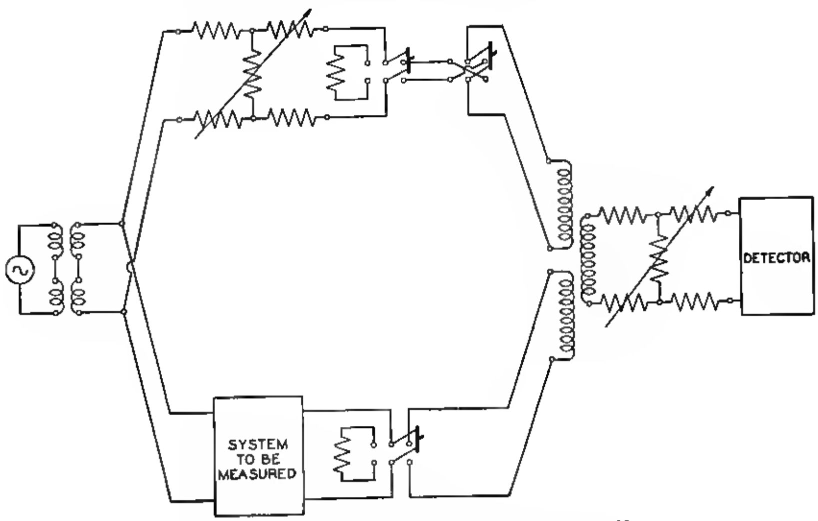

Fig. 1—Arrangement for measuring phase shift.

cally an arrangement of apparatus for measuring phase shift. Current of the frequency of measurement is sent through two paths, one con-

* The envelope delay is generally different from the phase delay which is the ratio of the phase shift to the frequency being considered, and should not be confused with it.

[10] W. P. Mason, U. S. Patent 1,684,403.

taining a resistance line (introducing only constant attenuation) and the other the system under consideration, to a detector which measures the magnitudes of the currents received from the two paths. Initially, by adjustment of the attenuation in the distortionless path the magnitudes of the two received currents are made the same. Then by operation of the switches the vector sum and difference of the two received currents can be measured. From the amount of attenuation introduced in the common path to the input of the detector to make the sum and difference equal, the difference in phase of the two received currents can be computed. This is the insertion phase shift of the system under consideration. This method of measurement has been only briefly described here, as all of its details are described in the patent referred to. This method does not involve an elaborate set-up of apparatus and gives accurate results, and is particularly useful where very small amounts of phase shift are involved.

2. *Measurement of Delay*

A number of measuring methods will now be described which vary somewhat in the amount of apparatus required and in the convenience with which the measurements can be made. The method of measuring envelope delay from impedance measurements is given first because of the very small amount of apparatus required, and for certain interesting steady-state phenomena which will appear in discussing the method of its operation. Following this, several modifications of a method will be referred to for determining the envelope delay from phase shift measurements. The application of this method and the determination of the results are usually quite laborious, but are given here since the apparatus required is fairly small in amount and usually readily available in a laboratory. When a number of delay measurements are to be made so that the saving of time during measurement is of importance, direct measurements of envelope delay can be made using somewhat complicated measuring circuits which require considerable time for building and calibrating, but which will allow measurements to be made simply with the loss of relatively little time. Several such circuits will also be considered.

a. Determination of Envelope Delay from Impedance Measurements

A method is given here for determining the envelope delay from steady-state impedance measurements. The method is limited to the measurement of systems which are capable of transmitting in both directions, and in certain cases it is further restricted in that both terminals of the system under test must be readily available at the

point where the test is conducted. The method is unsatisfactory for measuring extremely small amounts of envelope delay. It is particularly suitable for measurements on correcting networks in the field where special delay measuring apparatus is not available.

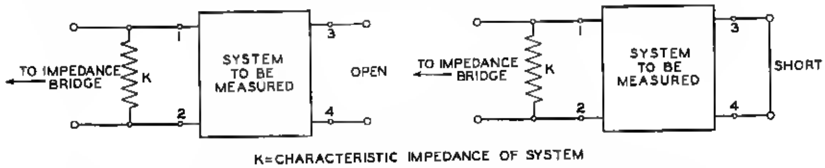

Fig. 2—Arrangement for special impedance measurements.

The system to be measured is connected to the impedance bridge as indicated in Fig. 2. The termination (short or open) used at the far end of the system constitutes a 100 per cent irregularity in its structure and the alternating current transmitted by the system from the impedance bridge to the far end is totally reflected at this irregularity and retransmitted by the system to its input terminals. When a steady-state has been established, this reflected current bears a definite phase relation to the incident current at the input terminals, this relation depending on the steady-state phase shift of the system at the frequency used for the measurement. This phase relation varies with frequency and, consequently, the measured impedance of the system will also vary with frequency. These variations in impedance are evident from the impedance-frequency curves plotted from the measurements taken, and it can be seen that the impedance varies cyclically over the frequency range.

To begin with we shall assume that the impedance bridged across the measuring trunk equals the characteristic impedance, K, of the system, as shown in the figure, and that the characteristic impedance is the same in both directions. Then if the variation of impedance completes one half cycle when the frequency is increased from f_1 to f_2 cycles, it is evident that the steady-state phase shift of twice the system is one half cycle greater at f_2 than at f_1. Now the envelope delay of a system in seconds at any frequency f is approximately

$$T_\Delta = \frac{\Delta B}{\Delta f},$$

where $\Delta B =$ the change in phase shift in cycles for a small change in frequency of Δf cycles per second. Here the change in the steady-state phase shift of the system is one quarter cycle for a finite change in frequency of $f_2 - f_1$. Dividing this change of phase shift by the change

of frequency gives for the envelope delay of the system

$$T_\Delta = \frac{1}{4(f_2 - f_1)} .$$

T_Δ here is not the envelope delay of frequency f_1 or of frequency f_2, but it is the envelope delay of some intermediate frequency. For our purpose, it is sufficiently accurate to assume that T_Δ is the envelope delay of the system at the frequency $(f_2 + f_1)/2$. The envelope delay of the system at any frequency can thus be determined from the impedance curves by making measurements over a sufficient frequency range to find the length in cycles per second of one half an impedance cycle with its mid-point at the frequency of which the delay is to be determined.

If a system has constant envelope delay and attenuation over the frequency range involved, then the impedance curves are periodic. The resistance and reactance curves are in quadrature with each other. The resistance and reactance curves for an open termination are 180° out of phase, respectively, with those for a short-circuit termination. In the usual case, however, there is attenuation in the system and this varies with frequency. The change caused by this attenuation in the impedance curves is in the amplitude of the impedance variations. The amplitude varies inversely with the attenuation of twice the system, expressed in terms of current ratio. Due to the variation of the envelope delay of the system with frequency, the length of an impedance cycle in cycles per second of frequency varies with frequency. The effect of this variable delay on the impedance curves is that the impedance cycles are concentrated more and more along the axis of the curve as the delay increases, the length of the impedance cycle varying inversely with the envelope delay of the network.

By way of illustration, Fig. 3 shows the computed impedance curves for short and open terminations on a 100-mile unit of phase corrector for 19-gauge, H-174 side circuit. Fig. 3 also gives the corresponding envelope delay-frequency curve. The characteristic impedance of this particular network is 600 ohms resistance. It will be noted that for this case the resistance curves for open and short terminations at the far end intersect on the line +300 ohms, while the corresponding reactance curves intersect on the zero line. The curve passing through the points of intersection of the curves for open and short terminations should be used as the axis for determining the length of impedance cycles. The delay obtained in this way is, of course, the delay of the system between its characteristic impedances.

When the characteristic impedance of the system under consideration is not the same for both directions, the delay obtained in this way is one half that of two such systems connected in tandem "back to back." Furthermore, when the impedance bridged across the measuring trunk

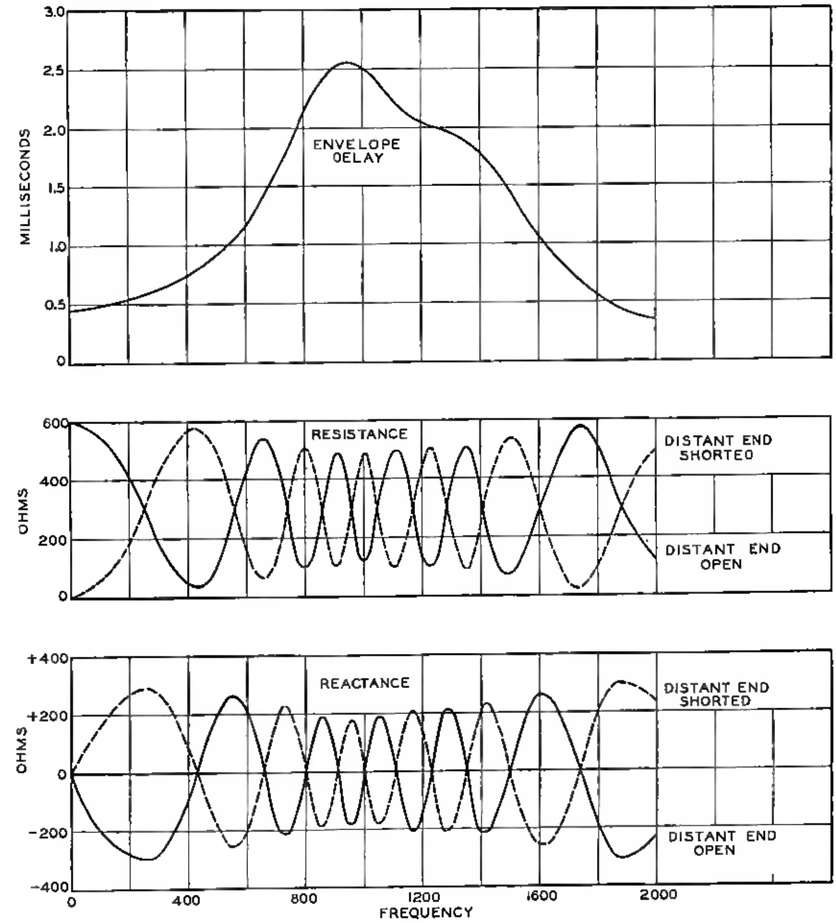

Fig. 3—Computed curves illustrating method of Fig. 2.

is not the characteristic impedance of the system being measured, then the delay measured is the insertion delay between two such impedances as the bridging impedance. Fundamentally, it is the periodicity of the difference of the impedance curves for open and short terminations which determines the insertion delay, and it follows that the periodicity obtained from the intersections of these curves gives the same delay.

The following method of measurement is given for those cases where the method already described is not sufficiently accurate because of the smallness of the impedance cycles for systems having large attenuations or delays.[11] It is assumed here that the characteristic impedance of the system is the same for both directions.

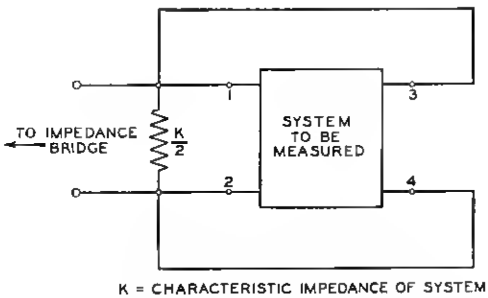

Fig. 4—Modified arrangement for special impedance measurements. (Open termination.)

Impedance measurements are made as before with the following changes as shown in Fig. 4: (1) $K/2$ is bridged across the measuring trunk in place of K; (2) instead of having the output of the network short-circuited or open, the output is bridged on the input. This case corresponds somewhat to the one above in which the open termination was used on the output of the system, with the exception that the return current now traverses the system only once in its complete trip from the bridge back to the bridge and, consequently, is attenuated and delayed only one half as much as before. These impedance curves are quite similar to those obtained above and may be interpreted in a similar manner. In this case, the envelope delay of the system in seconds at the frequency $(f_2 + f_1)/2$ cycles is, approximately,

$$T_\Delta = \frac{1}{2(f_2 - f_1)},$$

where $(f_2 - f_1)$ is the length in cycles per second of one half an impedance cycle of an impedance curve. Fig. 5 shows the computed impedance curves resulting from measurements made in this way on the same 100-mile unit of phase corrector and also gives the corresponding envelope delay-frequency characteristic of this network.

The case just described corresponds to the former case with the open end termination; that is, the results obtained are the same as those which would be obtained from the former case by using only one half

[11] D. K. Gannett, U. S. Patent 1,725,756.

of the system terminated at the far end in an open circuit. Impedance curves 180° out of phase with those obtained by the last method described can be obtained by using what is equivalent to one half of the system terminated at the far end in a short circuit. The circuit ar-

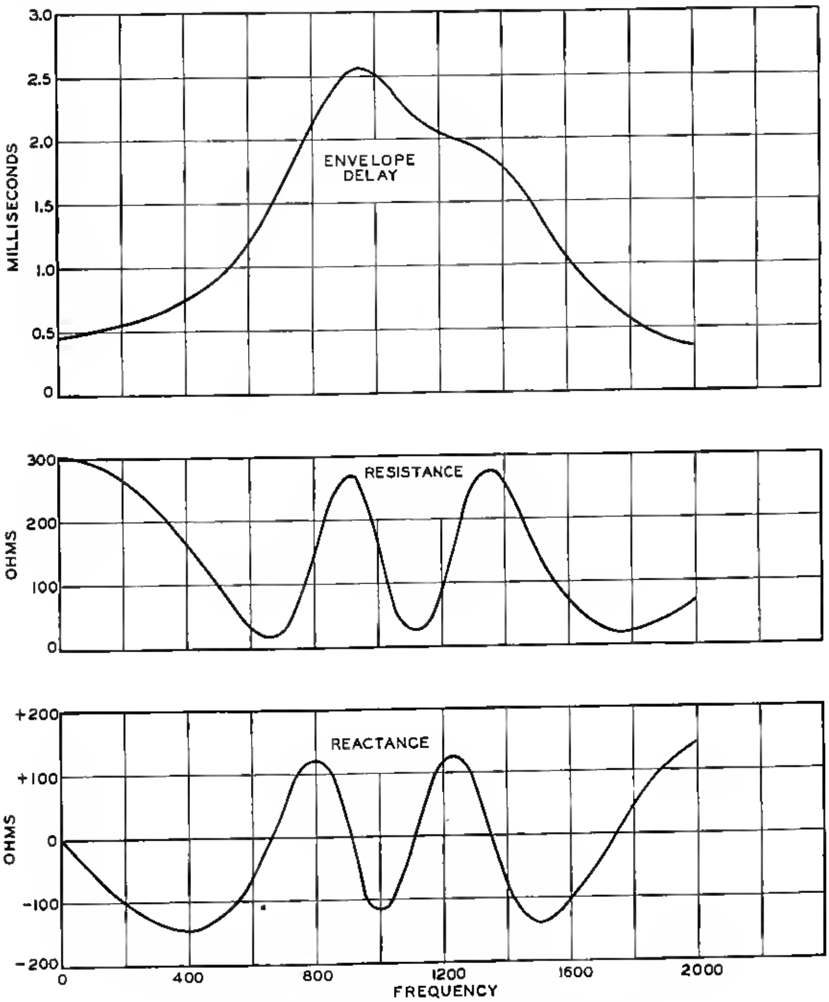

Fig. 5—Computed curves illustrating method of Fig. 4.

rangement for such measurements is given in Fig. 6. When the system being considered is balanced, the connections can be made as shown on the left. However, when the system is completely unbalanced, for example, a network built with no apparatus in one side

so that all points in this side of the network are at the same potential, the measurements may be made with the arrangements shown on the right of the figure. In the latter case, the measured impedance is four times that obtained for an equivalent system by the method shown on the left of the figure; and in plotting these values for comparison with those obtained by the method of Fig. 4, one fourth of the measured values should be used. The results obtained in this way are evident from what has already been described and will not be illustrated here.

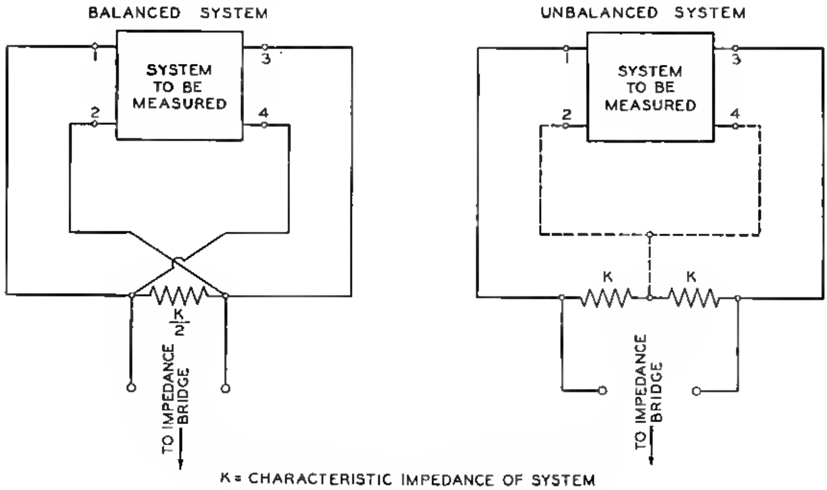

Fig. 6—Modified arrangement for special impedance measurements. (Short termination.)

As before, the curve passing through the points of intersection of the impedance curves corresponding to the open and short terminations should be used as the axis in determining the length of impedance cycles. For the network illustrated in Fig. 5, the resistance curves would intersect on the line +150 ohms, while the corresponding reactance curves would intersect on the zero line. The delay obtained in this way is the delay of the system between characteristic impedances. When other impedances are bridged across the measuring trunk than those shown in the figures, the delay measured is the insertion delay between impedances having the same relation to the actual bridging impedance as K has to the value of bridging impedance shown in the figures.

In most practical cases, the characteristic impedance of the network to be measured is a pure resistance and the network is designed to work between this impedance at each end. The value of resistance which

should be bridged across the measuring trunk to measure the delay of the network under these conditions is obvious from the above discussion. Sufficient accuracy can often be obtained by considering only the impedance curve obtained for either the open or the short termination and using the axis of this curve for determining the length of the impedance cycle; e.g., in Fig. 5 (which gives curves corresponding to the open termination) using the lines +150 ohms and zero as the axes of the resistance and reactance curves, respectively.

b. Determination of Envelope Delay from Phase Shift Measurements

Methods will now be briefly described for determining the envelope delay of a system from special measurements of the steady-state phase shift; that is, the difference in phase shift for a definite frequency difference or the difference in frequency for a certain difference in phase shift will be measured and the delay computed therefrom. Three measuring methods will be considered in which the fundamental principles involved are much the same. Practical circuits for measuring delay by these methods may be rather complicated from an apparatus standpoint in order to facilitate the measurements as much as possible. The details of these circuits are not given here, but they are disclosed in various patents.[12, 13, 14]

The following gives the essential principles on which these methods of measurement are based: The current of the measuring frequency from an oscillator traverses two separate paths and is then combined at the receiving end of the measuring circuit. In the first path no phase distortion is introduced, while in the second the frequency is transmitted through the system of which the delay is to be measured. Both paths contain resistance attenuators, so that the magnitudes of the currents received from the two paths may be adjusted as desired. If now a frequency is chosen such that the phase shifts through the two paths cause the two received frequencies to be exactly out of phase, an adjustment can be made so that an observer listening with a receiver to the combined received currents will hear no tone when the two received currents are equal in magnitude. If the frequency is now changed continuously, the observer will hear the tone increase and then decrease again to zero when the two received currents are again exactly out of phase, care being taken that the two received currents are kept equal in magnitude. This means then, that for this difference in frequency, the phase shift in the system under measurement has changed a complete cycle. From what has gone before it is simple to calculate

[12] U. S. Patent 1,596,941.
[13] H. Nyquist and H. A. Etheridge, Jr., U. S. Patent 1,596,942.
[14] S. B. Wright and K. W. Pfleger, U. S. Patent 1,596,916.

the approximate value of the envelope delay for the system under consideration.

In the three patents referred to, circuits for different purposes are given. In all of these methods both ends of the system to be measured must be available to the tester. The first describes a circuit in which the method of measuring is quite similar to that just described except that by means of a reversing switch the frequency interval is found corresponding to a change in phase shift of one half cycle. This method is suitable for measuring relatively large delays. The second circuit referred to is much the same as the first except that a definite phase shift can be introduced in the path which contains the system under consideration by means of a reactance inserted between two artificial resistance lines of considerable length. The method of operation is exactly the same as before except that here frequency intervals can be measured for changes in phase shift which are not integral multiples of one half cycle. This method is suitable for measuring much smaller values of delay than the first circuit referred to, but is not particularly suited to measuring very small delays. The third method is adaptable to measuring very small values of delay, such as those introduced by separate units of equipment. Here a phase shifter is introduced in the path containing the system under consideration and the change in phase shift through the system for a particular frequency interval is measured. The phase shifter for this purpose should be continuous in its operation; and in the circuit referred to, the relative phases of the received currents from the two paths are compared by means of a vacuum tube device which indicates a zero condition on a meter when the two received currents are in quadrature.

c. *Direct Measurement of Envelope Delay*

Here the phase shift of the envelope of a modulated wave is measured under steady-state conditions and this gives a direct measurement of the envelope delay when the measuring set is properly calibrated, inasmuch as the delay of the envelope of the modulated wave is closely related to the differences in phase shift for the component frequencies of the modulated wave transmitted. Before describing the details of the measuring circuits, some of the principles underlying the transmission of simple modulated waves will be considered; and for this purpose envelopes produced by sine wave modulations will be used. It is assumed in this discussion that the modulations in the transmitted current are repeated periodically and that the attenuation of the system used for transmission is completely equalized for all the frequency components.

Consider a 1000-cycle sine wave which is modulated by a 25-cycle sine wave in such a manner that the envelope just reaches zero once per cycle of the modulating wave. This wave is found on analysis to consist of three components, namely, 1000 cycles of two units amplitude, 975 cycles of one unit amplitude, and 1025 cycles of one unit amplitude. At the start, it is somewhat simpler to consider this case with the 1000-cycle component removed. In other words, the current transmitted through the system now consists of 975 and 1025 cycles in equal amounts. This value at the sending end may be conveniently written

$$\sin 975\,\overline{2\pi t} + \sin 1025\,\overline{2\pi t}.$$

The equivalent graphical expression is

$$2\cos 25\,\overline{2\pi t}\,\sin 1000\,\overline{2\pi t}.$$

Now suppose that the 975-cycle current suffers a phase change of β_{975} during transmission and that the 1025-cycle current suffers a phase change of β_{1025}, then the analytical expression for the current at the receiving end is

$$\sin(975\,\overline{2\pi t} - \beta_{975}) + \sin(1025\,\overline{2\pi t} - \beta_{1025}).$$

The corresponding graphical expression is

$$2\cos\left(25\,\overline{2\pi t} - \frac{\beta_{1025} - \beta_{975}}{2}\right)\sin\left(1000\,\overline{2\pi t} - \frac{\beta_{1025} + \beta_{975}}{2}\right).$$

In comparing the graphical expressions for the current at the sending end and the current at the receiving end, it is apparent that the only changes that have taken place are phase shifts of the 1000-cycle carrier wave and of the 25-cycle modulating wave. The phase shift of the 25-cycle modulating wave represents the actual delay of the deformation of the carrier wave. If the circuit is sufficiently long so that this phase shift amounts to one complete cycle, then the corresponding delay equals one period. For any other delay, the phase shift and delay are, of course, proportional. It will be apparent, therefore, that the delay may be represented by the following equation:

$$T_\Delta = \frac{\beta_{1025} - \beta_{975}}{2 \times 25\,(2\pi)} = \frac{\Delta\beta}{\Delta\omega},$$

where T_Δ is expressed in seconds, the numerator in radians and the denominator in radians per second. T_Δ, the value of the delay of this envelope, is according to our previous definition substantially the envelope delay.

This is the simplest form of transmitted current to which the term envelope delay can be applied. This type of wave, being made up of two sinusoidal components of equal magnitude, has the important property that its envelope suffers no distortion regardless of the length and complexity of the circuit as long as it has no non-linear element and as long as the two component frequencies are transmitted with equal attenuation.

Going back now to the original case of the 1000-cycle sine wave modulated by the 25-cycle sine wave where both sidebands and carrier are transmitted, the corresponding graphical expression for this current is

$$2(1 + \cos 25\, \overline{2\pi t}) \sin 1000\, \overline{2\pi t}$$

and the corresponding analytical expression is

$$2 \sin 1000\, \overline{2\pi t} + \sin 975\, \overline{2\pi t} + \sin 1025\, \overline{2\pi t}.$$

Now if the three components suffer phase changes equal to β_{975}, β_{1000}, and β_{1025}, the analytical expression for the wave at the receiving end is

$$2 \sin (1000\, \overline{2\pi t} - \beta_{1000}) + \sin (975\, \overline{2\pi t} - \beta_{975}) + \sin (1025\, \overline{2\pi t} - \beta_{1025});$$

and there is no simple corresponding graphical expression. It will be convenient to consider this wave as being made up of two components, one being the steady component

$$2 \sin (1000\, \overline{2\pi t} - \beta_{1000})$$

and the other being a variable component

$$2 \cos \left(25\, \overline{2\pi t} - \frac{\beta_{1025} - \beta_{975}}{2}\right) \sin \left(1000\, \overline{2\pi t} - \frac{\beta_{1025} + \beta_{975}}{2}\right),$$

which is the same as the total current discussed above. The outstanding complexity in this wave is the presence of a distortion which arises from the fact that the 1000-cycle carrier wave in these two components is not transmitted with the same phase change. The phase change of the 1000-cycle current, making up the steady component, is equal to β_{1000}, whereas the phase change in the variable wave is represented by

$$\frac{\beta_{975} + \beta_{1025}}{2}.$$

In other words, it is the average of the phase changes at 975 and 1025 cycles. Now, if it happens that these two expressions are equal, then there is no distortion. If, however, as is the general case, these expres-

sions are not equal, then there is a distortion which may be very easily exhibited by considering the case where the difference between $(\beta_{1025} + \beta_{975})/2$ and β_{1000} equals 90°. The current which then results is modulated by 50 cycles whereas the original wave was modulated by 25 cycles. Where the difference in question is intermediate in value between 0 and 90°, the detected modulating wave is complex, but has a component equal to 25 cycles. This component gradually gets smaller and disappears completely when 90° is reached. Now, if the circuit is made still longer, the 25-cycle component in the detected modulating wave again makes its appearance but has suffered a discontinuous shift of 180° in passing through the extinguishing point. By the time the phase difference in question has reached 180°, the received wave is distortionless except for the phase shift of 180° in the envelope which is not apparent, or at least is not distinguishable from a delay of one half cycle.

With this distortion in mind, it will now be apparent that the delay suffered by the modulated wave we are considering is no longer a definite quantity. However, it can be made definite for practical purposes by confining attention to the 25-cycle component of the envelope only. The distortion in question consists merely in adding other components to this one but does not shift its phase (except for the discontinuous change spoken of above). Consequently, for practical measuring purposes, if a device is used which eliminates the various harmonics of the 25-cycle current, this wave is perfectly definite for delay measuring purposes excluding the exceptional case where the fundamental component passes through zero.

These two forms of envelopes have been discussed in more or less detail because of the fact that they are the simplest ones for transmission without phase distortion. For this reason they have been used as the basis of the measuring devices which will now be described. The phase shift suffered by the envelope during transmission can be measured by comparison with a standard of the same frequency as the modulating frequency. This will be, of course, a direct measure of the envelope delay.

From the preceding discussion of some of the principles involved in the transmission of modulated waves, it is evident that the phase shift during transmission of the simple envelope considered is equal to one half the difference of the phase shifts of each of the sideband frequencies. This phase shift of the envelope is then the difference in phase shift for a definite frequency interval and is quite convenient for the measurement of the envelope delay. The envelope delay so measured is that for some frequency intermediate between the two

sideband frequencies and, although it is not accurately the envelope delay for the carrier frequency, it may be taken as such for all practical cases when the modulating frequency is taken small enough so that the slope of the phase shift-frequency curve for the carrier and the two sidebands may be considered constant.

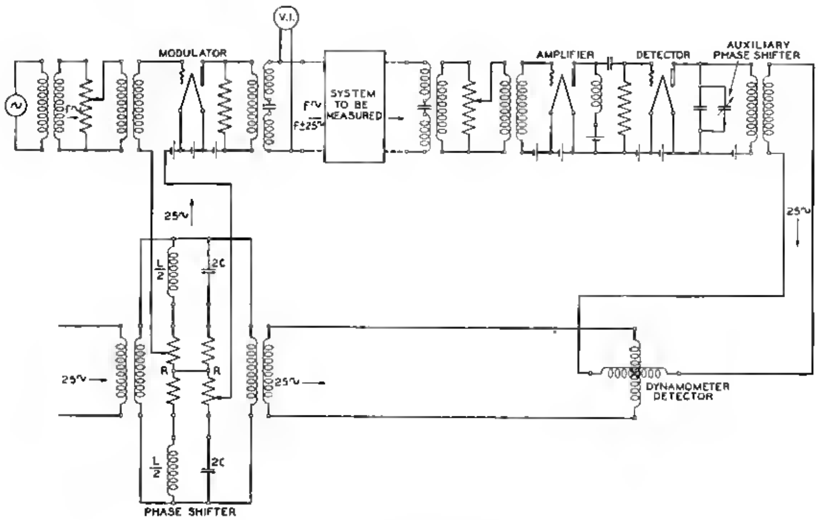

Fig. 7—Arrangement for direct measurement of envelope delay. In the phase shifter shown $R = 50\pi L = 1/50\pi C$.

Fig. 7 shows schematically a circuit for measuring the envelope delay by measuring the phase shift of the envelope.[15] The carrier frequency is modulated with another frequency, 25 cycles for example, and then transmitted through the system to be measured. At the receiving end an ordinary amplifier-detector is used to demodulate the received wave and obtain the modulating frequency. This source can then be compared in phase with a reference frequency which is obtained from the original source. In order to avoid including the effects of the measuring apparatus itself, the change in phase shift so measured through the system under consideration should be compared with a similar measurement made with an artificial resistance line substituted for the system under test. The difference of these two will, of course, be the phase shift suffered in the system by the envelope of the modulated current; and the envelope delay of the system in seconds at the carrier frequency, f, is then given approximately by

$$T_\Delta = \frac{1}{360}\frac{M}{p},$$

[15] U. S. Patent 1,645,618.

where p = the modulating frequency in cycles per second
and M = the phase shift of the envelope of the modulated wave in degrees.

In order to measure the value of M, some method of comparing the phases of various currents must be used. Also it is convenient to have in the measuring circuit a phase shifter or some means of controlling the phase of the modulating frequency.

The value used for the modulating frequency will vary somewhat with the frequency used for measurement and with the conditions under which the measurement is made. Of course, other things being equal, the greater the value of this modulating frequency the greater will be the frequency difference for which the phase shift is measured and the accuracy of the measurement will be correspondingly increased. This is true, however, only when the envelope delay is changing very slowly within this frequency interval. In most cases where the envelope delay is changing quite rapidly with frequency, it is necessary, therefore, to use as small a value for the modulating frequency as will give the required accuracy. In practice, both conditions of measurement will be encountered so that some sort of compromise value should be chosen for a particular measuring set which will do fairly well for its requirements. Various modifications of this circuit for loop and straightaway measurements are given in the patent referred to. Various methods of modulation and detection may be used.

(1) The set-up [16] shown in Fig. 7 has been used extensively for loop measurements on systems, including various telephone circuits and phase correcting networks. The details of the circuit of this set are not given here, but certain phases of its makeup and operation will be discussed. A frequency of 25 cycles from a tuning fork is used for modulation. In measuring the phase shift of the transmitted envelope, a dynamometer detector and phase shifter are used as described in the patent referred to.[15]

When the modulated wave as transmitted over the system is detected, the modulating frequency is obtained. This will, in general, differ in phase from the original modulating frequency. If the detected frequency and the original frequency are now put into the dynamometer detector, the phase of one of these frequencies can be shifted by means of the phase shifter until these two frequencies are 90° out of phase, which is indicated by zero reading of the dynamometer. The amount of phase shift which has been introduced in order to bring about this condition is a measure of the delay of the system being

[16] Compare "Phase Compensation III—Nyquist Method of Measuring Time Delay da/dw," E. K. Sandeman and I. L. Turnbull, *Electric Communication*, Vol. VII, p. 327, 1929.

measured. If the detector were balanced with a zero delay system and, then, rebalanced with the system under question inserted, the difference in these readings as given by the phase shifter would indicate the delay of the system. An integral multiple of π might not be taken care of in this measurement, but this is of little consequence.

For the modulating frequency of 25 cycles, a phase shift of nine degrees in the envelope of the 25-cycle modulation corresponds to a delay of .001 second. For convenience, therefore, the phase shifter used in this set is arranged in steps so that each step corresponds to a phase shift of nine degrees, or a delay of .001 second. In order to read intermediate values of delay, an auxiliary phase shifter, which

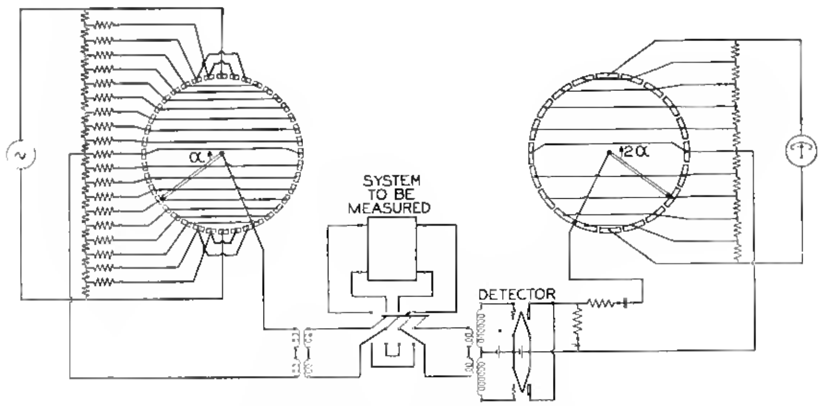

Fig. 8—Arrangement for direct measurement of envelope delay at low frequencies.

consists of a variable condenser bridged across the output circuit of the detector tube, is used and calibrated directly in steps of .0001 second.

This particular delay measuring set has been found quite useful in the frequency range of 300 to about 10,000 cycles per second. The absolute value of delay, of course, is not that which is measured, but this can usually be determined from the measured value by adding this measured value to the integral multiple of .04 second, which is suitable for the case in hand.

(2) For measurements below 300 cycles, the circuit arrangement shown in Fig. 8 can be advantageously used. This is based on principles exactly the same as those just described but differs considerably in the application of these principles.

Here a relatively low frequency must be used for modulation. One and a quarter cycles per second has been chosen because it is satisfactory for measuring at frequencies as low as 10 cycles and is easily ob-

tainable from a distributor driven by the 25-cycle tuning fork used in the measuring set described above. The frequency used here for modulation is exactly 1/20 that used in the other set.

Modulation is accomplished mechanically by means of a commutator and resistance potentiometer arranged as shown at the left end of the figure. The commutator brushes are rotated at a speed of 1¼ revolutions per second. The carrier frequency is connected to the potentiometer as shown so that the brushes as they pass over the commutator segments will pick off various voltages from the potentiometer, and on the completion of one revolution the resultant current at the output is equivalent to a cycle of complete modulation of the carrier such that both sidebands are transmitted with the suppression of the carrier frequency. The potentiometer has been designed with steps in such a way that, for all practical purposes, a modulation of pure 1¼ cycles is obtained, the higher harmonics in the modulated wave being so far removed from the fundamental and relatively so small that they are negligible.

As only the two sidebands of the modulated wave are transmitted here, the current which results from detection of this transmitted wave at the receiving end will have a frequency of 2½ cycles or twice the modulating frequency. Another set of commutator brushes is revolved over a set of segments, somewhat similar to that already mentioned, with a speed exactly twice that of the first, namely 2½ revolutions per second. The output of the detector is connected to these brushes and transmitted through the potentiometer shown connected to the segments of the commutator to a very sensitive galvanometer. The result of this arrangement is effectively a 2½-cycle modulation of the 2½-cycle current received from the detector and as a result of this modulation the current received by the meter will consist of a d.-c. component and a 5-cycle component, the relative amounts of each depending on the relation of the commutation to the phase of the received current. The brushes of the first commutator may be rotated at any instant relative to those of the second by a manual adjustment and their position relative to some arbitrary point noted. The galvanometer is arranged so that it does not respond readily to any except direct current. There is a particular position of the commutator brushes (and another 180 degrees removed from it) which will give no deflection in the galvanometer.

The particular details of measurement are considerably different from those of the preceding circuit, but in principle the arrangement is much the same. With a resistance line between the sending and receiving terminals the adjustable brushes are shifted until no deflec-

tion is obtained in the galvanometer. Then with the system to be measured inserted between the terminals of the measuring set, the brushes are again adjusted until the galvanometer shows no deflection. The setting in both cases can be noted by means of a suitable scale and the difference between the two settings for calibration and measurement is, of course, the phase shift of the envelope of the modulated wave in the system used for measurement. This scale can be calibrated in terms of seconds so that it measures the envelope delay directly. It is evident from the above description that a one-degree shift of the commutator brushes corresponds to an envelope delay of .00222 second.

This set has been found useful in measuring the phase distortion in circuits below 300 cycles per second, especially recently when considerable importance has been attached to the low-frequency distortion on circuits which have been developed for program transmission.

(3) When small amounts of distortion are to be measured and the frequency range will permit, a higher frequency may be used advantageously for modulation. Such a circuit, adapted for straightaway measurements, was used for checking up the phase correction of certain circuits used for television demonstrations.[4] The circuit arrangement has been described in the reference given.

In this particular case, it was not expected that the distortion of the overall system including the phase correction would be very great, so that the chief point of interest in these measurements was the detection of small changes in delay over the relatively large frequency range concerned. The modulating frequency used was 250 cycles per second, this larger value being used to obtain the desired accuracy. The frequency required for reference at the receiving end was provided by sending the modulating frequency over another circuit in the same manner as that used on the circuit being measured, except that a constant frequency for the carrier was used in the reference circuit. The purpose of this was to introduce approximately the same delay in the reference circuit as in the measured circuit because of the fact that the phase shifter used at the receiving end was capable of measuring only small differences in phase.

d. Direct Measurement of Delay of Envelope

Instead of measuring the envelope delay, which is $d\beta/d\omega$ by definition, it may sometimes be desirable to measure the delay of the envelope, say, the interval between the instant of application of a sinusoidal wave and the instant of the received wave reaching a predetermined value. One suitable arrangement which may be utilized to

this end has been described by Herman.[17] His description, particularly his Fig. 2, should make it unnecessary to describe it here.

Some Results Obtained by Various Methods of Measurement

In the accompanying figures results will be given in graphical form of various results which have been obtained from using the measuring

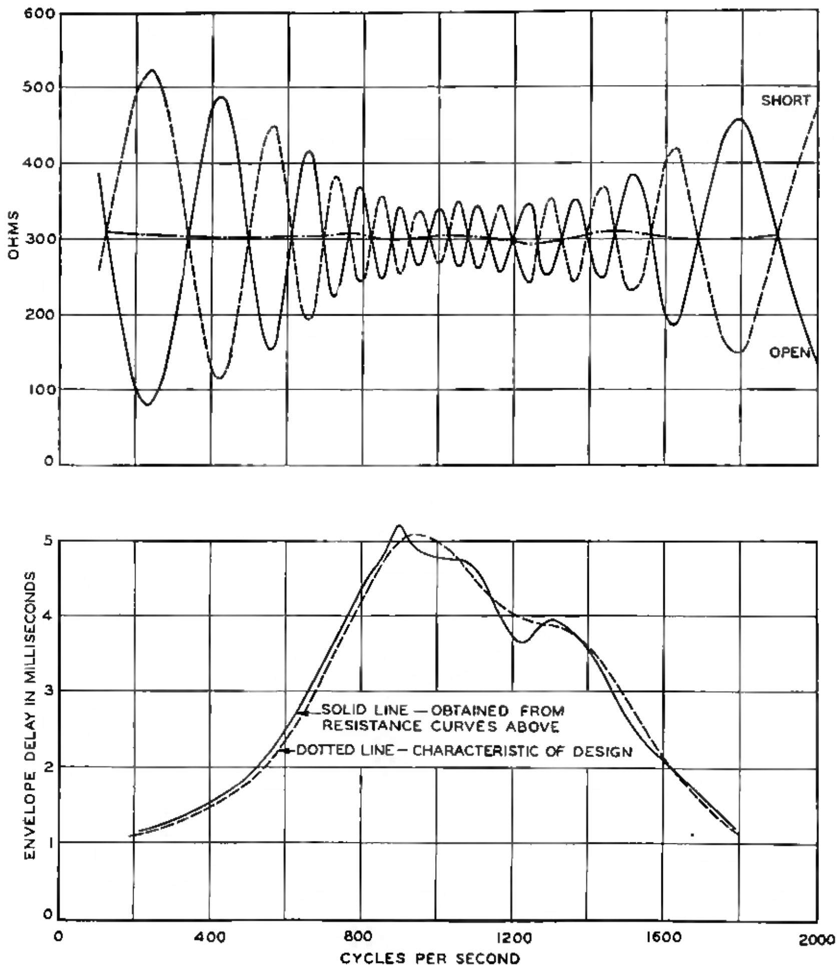

Fig. 9—Results of impedance measurements on phase corrector for 200 miles of 19-ga. H-174 side circuit.

devices described above on actual telephone circuits or networks designed to be associated with them. The values added to the meas-

[17] "Bridge for Measuring Small Time Intervals," J. Herman, *B. S. T. J.*, Vol. VII, p. 343, 1928; particularly application No. 2, p. 349.

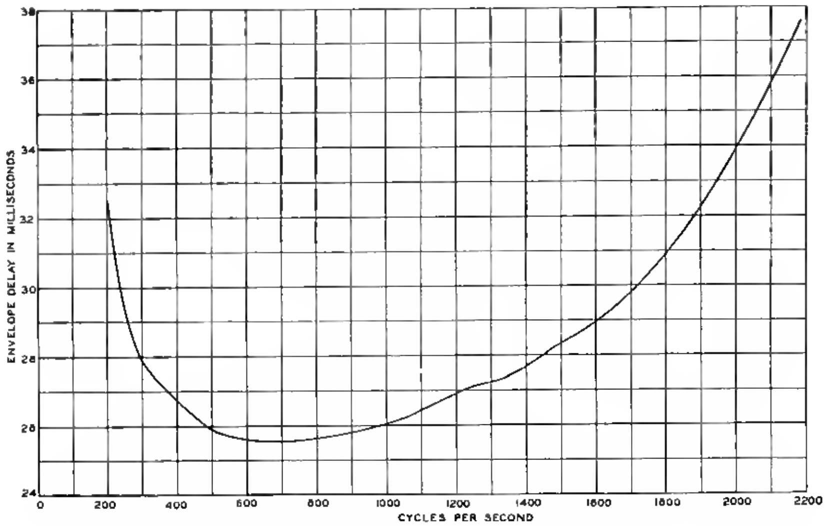

Fig. 10—Envelope delay characteristic for 231 miles of 19-ga. H-174 side circuit.

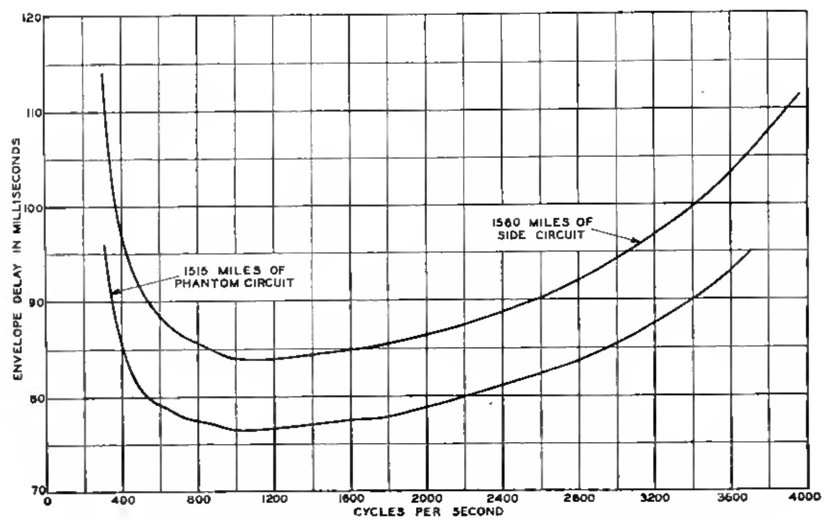

Fig. 11—Envelope delay characteristics for 19-ga. H-44-25 circuits.

ured values to give the absolute values of envelope delay shown on the curves are obtained from an approximate estimate of the delay of the system under consideration.

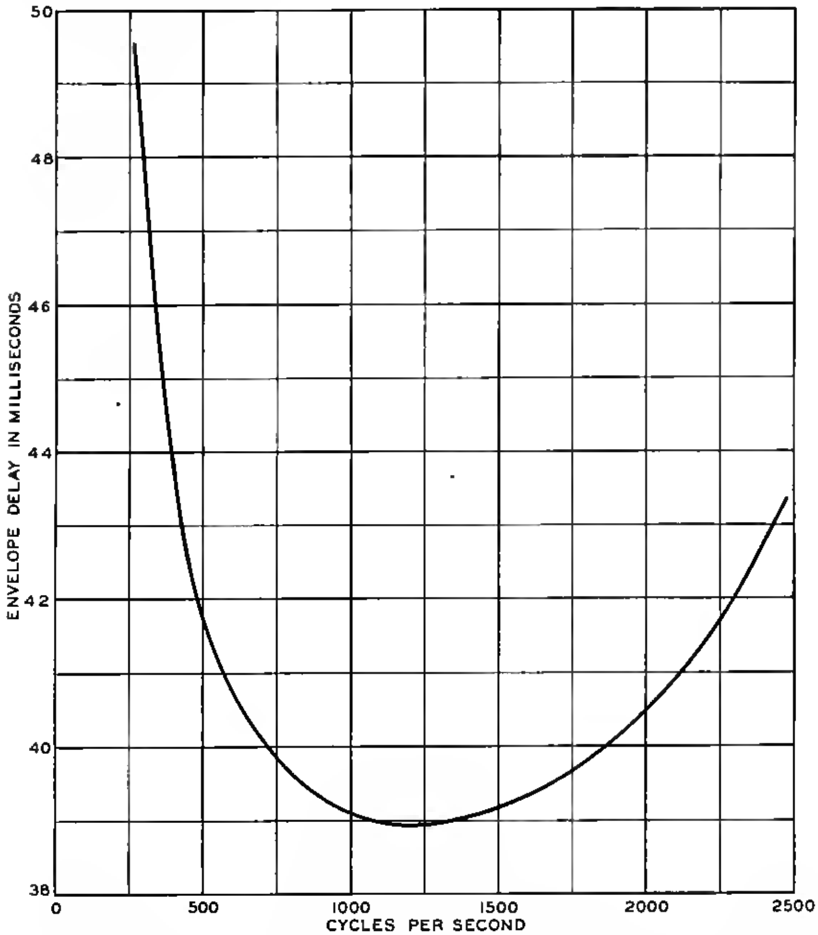

Fig. 12—Envelope delay characteristic for 708 miles of 16-ga. B-22-N two-wire circuit.

No data are given here to show the results of measurements by the method of Fig. 1. This circuit is particularly useful in the measurement of networks and many examples of data obtained in this way are included in another paper.[7]

Fig. 9 shows the results of impedance measurements made as shown in Fig. 2 on a phase correcting network which was designed to equalize the delay for 200 miles of 19-gauge H-174 side circuit for picture trans-

mission. In the upper part of the figure the resistance-frequency curves are shown and the envelope delay-frequency curve derived therefrom is shown in the lower part of the figure. The delay characteristic for which this particular network was designed is also shown for comparison and gives a rough idea of the accuracy of this method of measurement.

No figures are shown here which give the results of measurements made by the methods referred to for determining envelope delay from special phase shift measurements. Although the actual methods of

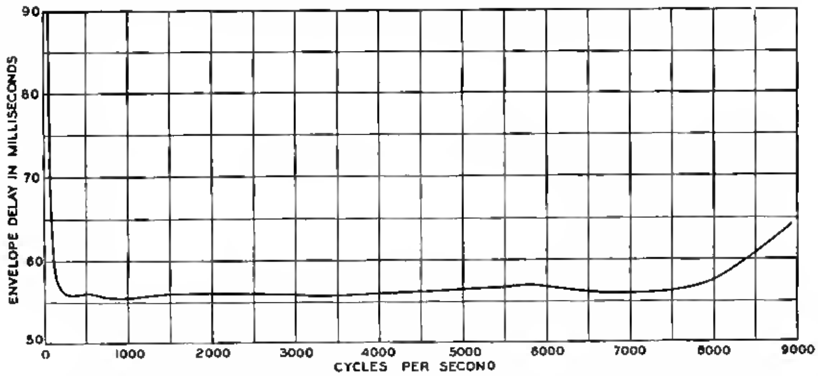

Fig. 13—Envelope delay characteristic of 737 miles of 16-ga. B-22-N program circuit.

measurement in these cases are quite different from the impedance measurement method, the delay results are obtained in a similar manner, and these have just been illustrated by the figure above.

Figs. 10, 11 and 12 show the results of direct measurements of the envelope delay, using the method described above which has a modulating frequency of 25 cycles per second. Fig. 10 gives the measured envelope delay-frequency characteristic for 231 miles of 19-gauge H-174 side circuit. Fig. 11 gives the envelope delay-frequency characteristics as measured for approximately 1560 miles of 19-gauge H-44-25 side circuit and for approximately 1515 miles of 19-gauge H-44-25 phantom circuit. Fig. 12 gives the corresponding characteristic for 708 miles of 16-gauge B-22-N two-wire circuit.

Fig. 13 gives the envelope delay-frequency characteristic for 737 miles of 16-gauge B-22-N cable circuit equipped with phase correctors for program transmission.[13] The measurements for frequencies above 300 cycles per second were made with the measuring device using a modulating frequency of 25 cycles while the measurements below 300

[13] "Long Distance Cable Circuit for Program Transmission," A. B. Clark and C. W. Green. To be presented at Summer Convention of A. I. E. E. at Toronto, June 1930.

were made with the set which used $1\frac{1}{4}$ cycles as the modulating frequency.

Fig. 14 shows the measured envelope delay-frequency characteristic for a special open-wire circuit [4] used for a television demonstration between Washington, D. C. and New York, N. Y. Curves are shown for measurements on the circuit alone and for the circuit equipped with its dry weather equalizer. The curves do not appear to be as smooth as the curves shown in the above figures, but this is largely due to the difference of the scales used for plotting the measurements. However,

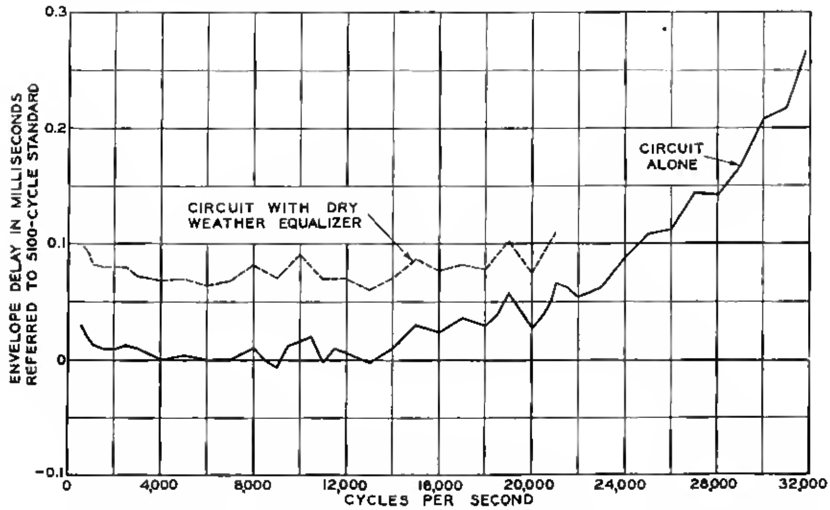

Fig. 14—Envelope delay characteristic for special open-wire circuit; Washington, D. C.—New York, N. Y.

some of the irregularity is due to the method of measurement and the fact that noise on the open-wire circuits obscured somewhat the exact point of balance.

Conclusion

It has not been the intent of this paper to include all the known methods of measuring phase distortion. Various methods for measuring phase shift are, of course, known and these can often be used to indicate phase distortion. In a practical way on telephone circuits, the term defined as envelope delay has certain advantages, and the paper is chiefly concerned with methods of measuring this quantity. In order to avoid including information which is contained elsewhere, the methods have not been given in detail; but references have been given, when possible, to sources where more detailed information can

be found. In setting up any of these circuits for actual use, certain precautions must be taken which will soon be evident. One particular point that might be mentioned here is the fact that the phase distortion introduced by the apparatus necessary for amplifiers and particularly detectors varies somewhat with the amount of power being transmitted through it, and this consideration must be given weight.

Keys, switches, and such apparatus may be introduced for the convenience of the tester. The amount of amplification and the sensitivity of the detectors used depend somewhat on the accuracy required of the measurement.